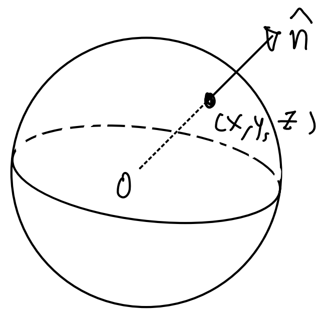
Orientation of Surfaces

To integrate vector fields over surfaces, we need

> **Def 17** (Orientation of a surface in $\mathbb{R}^3$)
>
> A surface S is orientable if one can define a unit normal vector field continuously at every point of S.
>
> (Such a chosen normal vector field is called an orientation of S)

eg 57: (i) $S^2 = \{x^2+y^2+z^2=1\}$



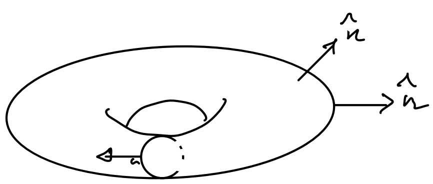
$\hat{n} = x\hat{i} + y\hat{j} + z\hat{k}$ is cts

$(\|\hat{n}\| = \sqrt{x^2+y^2+z^2} = 1)$

$\therefore$ S is orientable

(and the chosen $\hat{n}$ is called an orientation)

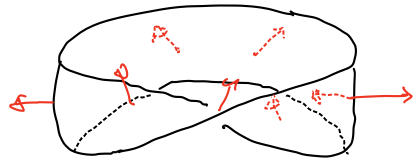
(ii) Torus



orientable

(iii) Möbius strip

is not orientable



(usually refered as a surface of one side)

Remark: Parametric surface $S = \vec{r}(u,v)$ are always orientable:

the unit normal vector field $\hat{n} = \dfrac{\vec{r}_u \times \vec{r}_v}{\|\vec{r}_u \times \vec{r}_v\|}$ given by

the parametrization is a continuous unit normal vector field on S.

($\vec{r}_u, \vec{r}_v$ "continuous" tangent vectors $\Rightarrow$ $\vec{r}_u \times \vec{r}_v$ is a "continuous" normal vector

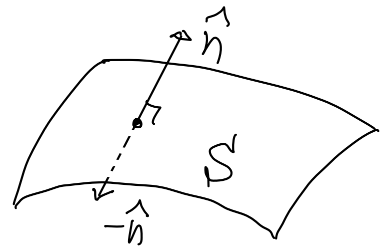
$\|\vec{r}_u \times \vec{r}_v\| \neq 0 \Rightarrow \dfrac{\vec{r}_u \times \vec{r}_v}{\|\vec{r}_u \times \vec{r}_v\|}$ continuous unit normal vector field)

Terminology

Given a connected orientable surface $S \subset \mathbb{R}^3$, there are

two ways to assign the continuous unit normal vector field

Suppose S is orientable and we have already chosen one continuous unit normal vector field $\hat{n}$, before choosing a parametrization.



Refl: We said that a parametrization $\vec{r}(u,v)$ of S is compatible with the orientation $\hat{n}$ of S given by the unit normal vector field if $\hat{n} = \dfrac{\vec{r}_u \times \vec{r}_v}{|\vec{r}_u \times \vec{r}_v|}$.

(The chosen unit normal vector field is also referred as the orientation of S)

Def 19: Let S be orientable with unit normal $\hat{n}$ (continuous).

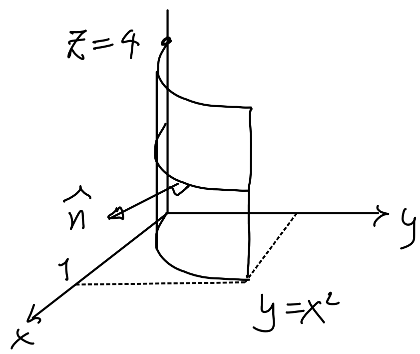
Let $\vec{F}$ be a vector field on S.

Then the flux of $\vec{F}$ across S is

$$\text{Flux} = \iint_S \vec{F} \cdot \hat{n}\, d\sigma$$

eg 59: S:

$$y = x^2, \quad 0 \le x \le 1, \quad 0 \le z \le 4$$



with $\hat{n}$ given by the natural parametrization

$$\vec{r}(x,z) = x\hat{i} + x^2\hat{j} + z\hat{k}$$

Let $\vec{F} = yz\hat{i} + x\hat{j} - z^2\hat{k}$

Find $\iint_S \vec{F} \cdot \hat{n}\, d\sigma$

Soln: To calculate $\hat{n} = \dfrac{\vec{r}_x \times \vec{r}_z}{\|\vec{r}_x \times \vec{r}_z\|}$, we have

$$\begin{cases} \vec{r}_x = \hat{i} + 2x\hat{j} \\ \vec{r}_z = \hat{k} \end{cases} \Rightarrow \quad \vec{r}_x \times \vec{r}_z = 2x\hat{i} - \hat{j} \quad \text{(check!)}$$

$$\Rightarrow \quad \hat{n} = \frac{2x\hat{i} - \hat{j}}{\sqrt{4x^2+1}}$$

Then $\iint_S \vec{F}\cdot\hat{n}\, d\sigma = \int_0^4\int_0^1 \underbrace{(yz\hat{i}+x\hat{j}-z^2\hat{k})}_{\vec{F}}\cdot \underbrace{\frac{2x\hat{i}-\hat{j}}{\cancel{\sqrt{4x^2+1}}}}_{\hat{n}} \underbrace{\cancel{\sqrt{4x^2+1}}\, dx\, dz}_{d\sigma}$

$$= \int_0^4\int_0^1 (2x^3z - x)\,dx\,dz = 2 \quad (\text{check!}) \quad \#$$

Remark: $\iint_S \vec{F}\cdot\hat{n}\,d\sigma = \iint_{(u,v)} \vec{F}(\vec{r}(u,v))\cdot \frac{\vec{r}_u\times\vec{r}_v}{\|\vec{r}_u\times\vec{r}_v\|}\,\|\vec{r}_u\times\vec{r}_v\|\,du\,dv$

$$= \iint_{(u,v)} \vec{F}(\vec{r}(u,v))\cdot \underbrace{(\vec{r}_u\times\vec{r}_v)\,du\,dv}_{\parallel}$$

($\hat{n}\,d\sigma$ is called the <u>oriented area element</u>)

<u>Thm 12</u> (<u>Stokes' Theorem</u>)

Let S be a piecewise smooth <u>oriented</u> surface with piecewise smooth boundary C (including the case that C is a union of finitely many curves). Let

$\vec{F} = M\hat{i} + N\hat{j} + L\hat{k}$ be a C^1 vector field.

Suppose C is <u>oriented anti-clockwisely with respect to</u> the <u>unit normal vector field</u> $\hat{n}$ on S. Then

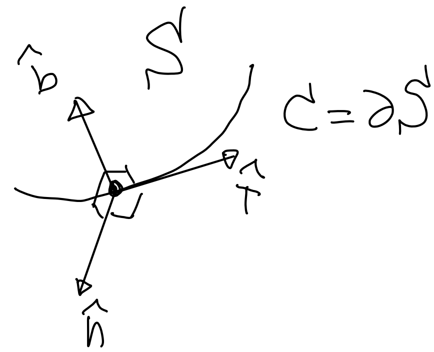
$$\oint_C \vec{F}\cdot d\vec{r} = \iint_S \operatorname{curl}\vec{F}\cdot\hat{n}\,d\sigma = \iint_S (\vec{\nabla}\times\vec{F})\cdot\hat{n}\,d\sigma$$

Here : (i) if $C = C_1 \cup \cdots \cup C_k$, then it means

$$\sum_{i=1}^{k} \oint_{C_i} \vec{F} \cdot d\vec{r} = \iint_S (\vec{\nabla} \times \vec{F}) \cdot \hat{n} \, d\sigma$$

(ii) "C is oriented anti-clockwisely with respect to the unit normal vector field $\hat{n}$" means that we choose the <u>direction</u> of C such that its (unit) tangent vector $\hat{T}$ satisfies

$$\boxed{\hat{b} = \hat{n} \times \hat{T} \text{ pointing } \underline{\text{toward}} \text{ the surface } S}$$

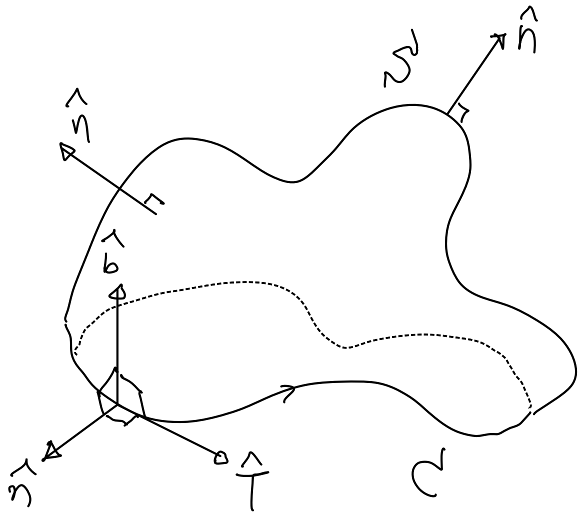


i.e. the unit vector $\hat{b}$ tangent to S, normal to C and pointing toward S satisfies

$$\boxed{\hat{T} = \hat{b} \times \hat{n}}$$

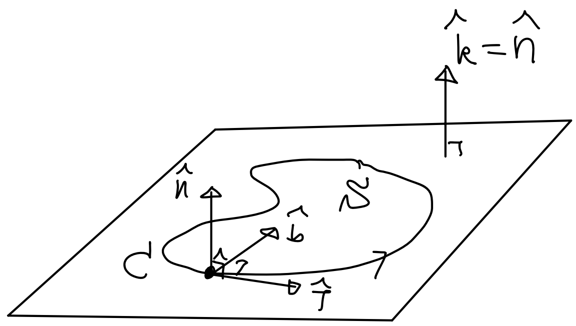
eg 60

(1)



(2) $S \subset \mathbb{R}^2$ with $\hat{n} = \hat{k}$

same as the usual anti-clockwise direction of a closed plane curve.



(3) (to be cont'd)